



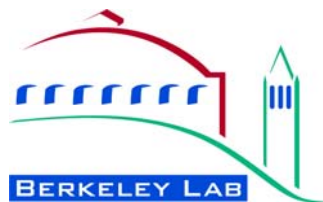
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DROUGHT ANALYSES OF THE CALIFORNIA CENTRAL VALLEY SURFACE-GROUNDWATER CONVEYANCE SYSTEM

PIER FINAL PROJECT REPORT

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Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

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- Transportation

Drought analysis of the California Central Valley Surface-Groundwater-Conveyance System is the final report for the Development and Application of a California Basin Water-Energy Model project (Contract Number 500-02-004, Work Authorization Number 040) conducted by the Lawrence Berkeley National Laboratory and the University of California, Berkeley in collaboration with the California Department of Water Resources. The information from this project contributes to PIER's Energy-Related Environmental Research Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

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Abstract

To understand how surface and groundwater supplies in California's Central Valley would respond to prolonged drought conditions, researchers conducted a series of model simulations based upon historic data and a range of drought conditions from mild to severe for time periods lasting up to 60 years. Land use, agricultural cropping patterns, and water demand were fixed at the 1973-2003 mean and water supply decreased by effective amounts ranging between 25 and 50 percent for the Central Valley, representing light to severe drought types. The analysis specifically examined four basins within the Central Valley: the Sacramento Basin, the San Joaquin Basin, the Tulare Basin, and the Eastside Drainage. Model results suggest the greatest impacts are in the San Joaquin and Tulare Basins, regions that are heavily irrigated. Surface diversions decreased by as much as 42 percent in these regions. Stream-to-aquifer flows reversed and aquifer storage dropped. Most significant was the decline in groundwater head for the severe drought cases, where results suggest the water table is unlikely to recovery within the foreseeable future. However, the overall response to such droughts is not as severe as anticipated and the northern Central Valley may act as groundwater insurance to sustain California during extended dry periods.

Keywords: California, surface-groundwater model, drought scenarios, agricultural water supply, Central Valley.

Executive Summary

Introduction

Although California has a history of long-drought conditions since the last glacial epoch 11,000 years ago, the past 150 years have brought a slightly above average wet regime. This recent wet regime has experienced at least 11 short drought periods, including the 1929 – 1934 drought which has been the benchmark for storage capacity and yield when designing large reservoirs in California. When evaluating the future of water resources in response to the changing climate, however, this benchmark drought is expected to be exceeded. The response of resource management practices to this shift in standards will depend on the amount of information available regarding the capabilities and limits of the state's resources.

Purpose

This study provides information about the response of California's water resources to long-term droughts associated with climate change. The models will aid policy makers by predicting the limits and capabilities of California's water resource. These models examine features of California's water resources individually as well as collectively, allowing researchers to identify localized issues and assess their overall impact.

Project Objectives

To simulate Central Valley water conditions under a severe drought, this project used the Department of Water Resources' water flow and allocation models—the California Central Valley Groundwater–Surface Water Simulation Model and the California Simulation Model. These models simulate groundwater pumping and water use based upon historic data. This report focuses on four heavily irrigated basins within the Central Valley: the Sacramento Basin, the San Joaquin Basin, the Tulare Basin, and the Eastside Drainage (east Sacramento region).

Specifically, this study accomplished these research objectives:

- Determined how long term droughts will impact water supply.
- Illustrated potential for surface and subsurface storage.
- Examined whether groundwater compensates for reductions in surface inflow.
- Determined the extent that the water table is reduced during, and following, long- term droughts.
- Predicted how, when, and if the system recovers or reaches a new equilibrium.

Project Outcomes

The long-term droughts simulated in this study as surface flow reductions ranged from 30 percent (light) to 70 percent (severe) for periods ranging from 10 to 60 years. In response to these drought scenarios, the overall surface diversions decreased by as much as 42 percent and stream-aquifer flows (where groundwater contributes to surface water flows) reversed due to

decreased stream flow and increased groundwater pumping. Most significant is the decline in groundwater levels for severe drought cases, which in some cases is unlikely to recover. Groundwater levels are simulated with a 30-year recovery period, with some individual basins responded differently. The San Joaquin basin recovers most rapidly, while the Tulare basin and Eastside drainage recover much less quickly, with some recovery rates suggesting that the Tulare Basin may never recover from the most severe drought scenario. Other regions experience more rapid rates of groundwater recovery and would likely reach pre-drought groundwater levels relatively rapidly after a drought.

Conclusions

This study illustrates that the impacts of climate change and long-term drought will likely deplete aquifers, increase electricity demand (pumping), and decrease hydropower generation. The severity of these impacts will depend on the recoverability of groundwater aquifers and an understanding of their capabilities.

Recommendations

This report provides specific information about the response of water resources to climate change, to policy makers and scientists for determining how to respond to these issues. Further investigation into the subject, perhaps using slightly different parameters, is also suggested.

Benefits to California

This report provides valuable information and forecasts regarding California's water supply and use. Understanding the response of the water system to a range of drought scenarios will aid policy makers in managing climate change impacts on water supply.

Note: All tables, figures, and photos in this report were produced by the authors, unless otherwise noted.

1.0 Introduction

The western United States has experienced periods of long drought conditions since the last glacial epoch 11,000 years ago. The period between 900 and 1400 A.D. was a time when severe long duration droughts occurred in the western U.S. This medieval mega-drought period was followed by a less severe drought period that was coincident with the Little Ice Age cooling period. Samples from sediments, tree rings, and tree stumps, combined with isotope dating analysis have been used to reconstruct these naturally occurring droughts that lasted 50 to more than 100 years (Stine 1994; Herweijer et al. 2006; Cook et al 2007). Indeed, two epic drought periods; one lasting from approximately 900 to 1100, and the second lasting from about 1200 to 1350, contributed to the decline and disappearance of the Anasazi people, a culture that relied on irrigated agriculture to support its population. Drought is also seen as a contributing factor in the failure of European colonies in South Carolina and North Carolina in the 1500s.

During the last 150 years, California has been in a slightly above average wet regime, with at least 11 short-duration drought periods (Ingram et al. 1996; Cook et al. 2004). The 1929-1934 drought has traditionally been the benchmark event used for designing storage capacity and yield of large California reservoirs. However, the California Department of Water Resources (DWR) and other water agencies have begun to evaluate new approaches for managing water resources in response to the changing climate (DWR 2006) and anticipate that this historic drought may be exceeded.

The goals of this study are to quantify the impacts of long-term droughts — an analogue for climate change related snowpack reduction — on water supplies, and to illustrate the potential for surface and subsurface storage to limit the adverse impacts of drought and snowpack reduction on water supply. This includes how groundwater pumping compensates for reductions in surface inflow, the extent in which the water table is reduced, and how, when, and if this system recovers or reaches a new equilibrium. In the next section, the authors provide details on our approach for simulating persistent droughts in the California Central Valley. This is followed by the results and discussion section, then our summary and conclusions.

2.0 Approach

Analysis of California Central Valley impacts of sustained droughts are based in this study on a series of specified reductions in surface flows corresponding to historical 30% (below average), 50% (dry), and 70% (critically dry) effective reductions, for periods ranging from 10 to 60 years, based on historical dry periods and simulated through the California Simulation model (CALSIM) II, then applied to the DWR's California Central Valley Groundwater-Surface Water Simulation Model (C2VSIM) to set boundary conditions for surface water inflows. This simplified methodology represents a means to evaluate the impacts of reductions in net surface flow from reservoirs and Central Valley precipitation.

The DWR is addressing global climate change in the California Water Plan, Bulletin 160, (DWR 2005a). Specified drought scenarios act as an analogue to projected reductions in snowpack surface flows. Rather than focus on causes of global climate change, which are being addressed by other agencies and research institutions, the DWR Water Plan looks at potential impacts of climate change on water resources in California and strategies for adapting to these changes.

2.1. Model Descriptions

The DWR water flow and allocation models, the California Central Valley Groundwater-Surface Water Simulation Model (C2VSIM) and the California Simulation model (CALSIM) were used for this study.

California Central Valley Groundwater-Surface Water Simulation Model (C2VSIM) was developed as a California Central Valley application of the DWR's Integrated Water Flow Model (IWFModel: DWR 2005b, 2005c, 2006). Integrated Water Flow Model simulates land-surface processes, surface water flow and groundwater flow. The land-surface module computes infiltration and runoff from net precipitation; consumptive use by native vegetation, irrigated crops and urban areas; surface water diversion and application; groundwater pumping and application; infiltration and return flow from irrigation; and recharge. Surface water flow is simulated as a function of flow from upstream reaches, tributaries and lakes; surface runoff; agricultural and urban return flows; diversions and bypasses; and exchanges with the groundwater flow system. Horizontal and vertical groundwater flow are simulated using the Galerkin finite element method and a quasi-three-dimensional approach utilizing the depth-integrated groundwater flow equation for horizontal flows in each aquifer layer and leakage terms for vertical flow between aquifer layers. To the extent that is practical, Integrated Water Flow Model directly incorporates readily available historical and spatial data sets, including precipitation, the Natural Resource Conservation Service (NRCS) runoff curve number, surface water inflows and diversions, land use and crop acreages.

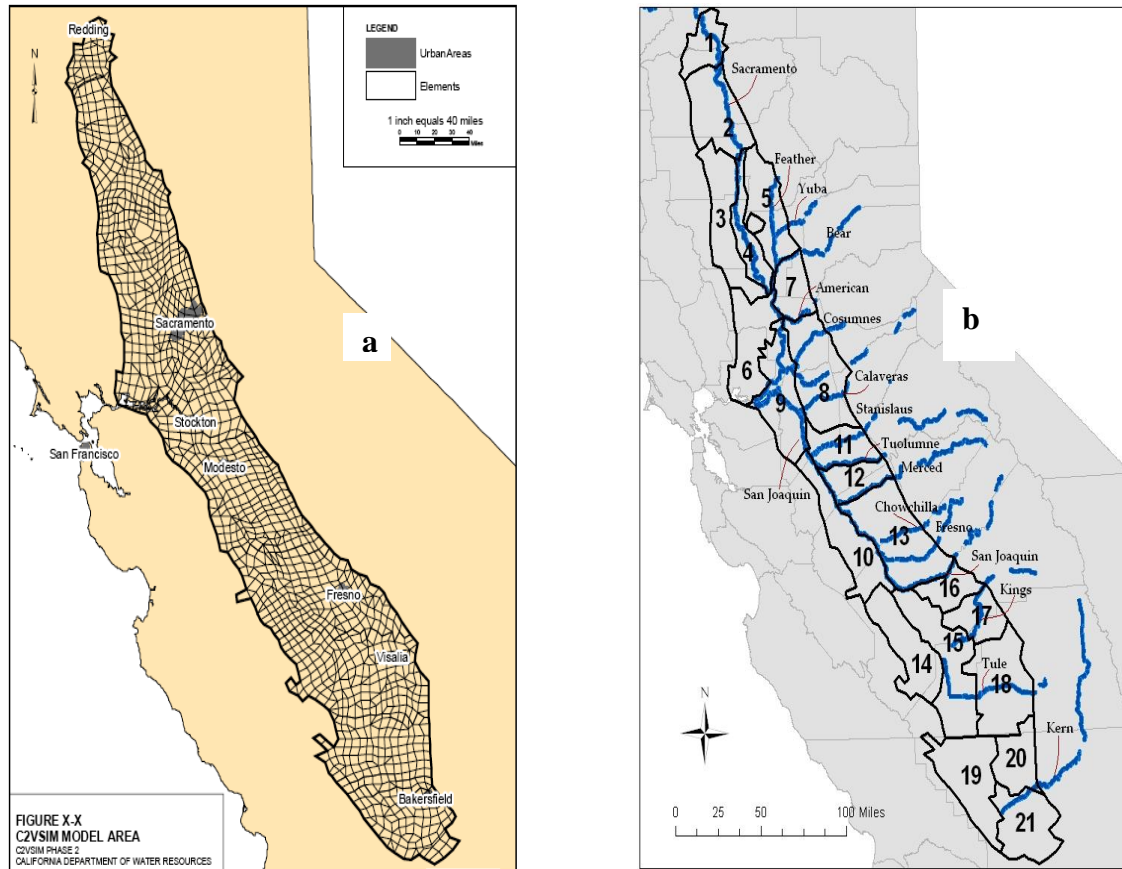


Figure 1. C2VSIM II (a) fine grid and (b) sub-basins.

The California Central Valley Groundwater-Surface Water Simulation Model II model simulates land surface processes, groundwater flow and surface water flow in the alluvial portion of the Central Valley (Fig. 1) using a monthly time step. California Central Valley Groundwater-Surface Water Simulation Model II covers an area of approximately 7,722 square kilometers (km²), about 20,000 mile², and incorporates 1392 nodes forming 1393 elements and three layers, 431 stream nodes delineating 74 stream reaches with 97 surface water diversion points, two lakes, and eight bypass canals (Fig. 1a). Surface water inflows are specified for 35 gauged streams and simulated for ungauged small watersheds. The model area is divided into 21 sub-regions (Fig. 1b), where each sub-region is treated as a ‘virtual farm’ for allocating groundwater and surface water to meet water demands in the land-surface process. California Central Valley Groundwater-Surface Water Simulation Model II was calibrated to match observed groundwater heads and surface water flows from October 1975 through September 1999.

The model was run with a monthly time step from October 1972 to September 2003. Regional-scale parameter values were calibrated using the Parameter Estimation (PEST) program (Doherty, 2005) to match semi-annual groundwater head observations at 121 locations and monthly surface water flow observations at nine locations from October 1975 to September 1999, and average monthly stream-aquifer interaction values at 65 locations.

The California Simulation Model version II (CALSIM II) is a general-purpose, network flow, reservoir and river basin water resources simulation model developed jointly by the California Department of Water Resources and the U.S. Bureau of Reclamation (Draper et al. 2004). It is used for evaluating operational alternatives of large, complex river basins. California Simulation model integrates a simulation language for flexible operational criteria specification, a mixed integer linear programming solver for efficient water allocation decisions, and graphics capabilities for ease of use. A linear objective function describes the priority in which water is routed through the system and the constraints set the physical and operational limitations toward meeting the objective. California Simulation model maximizes the objective function in each time period to obtain an optimal solution that satisfies all constraints.

California Simulation model was originally designed, and has been successfully implemented as a planning tool for the State Water Project (SWP) and Central Valley Project (CVP) to examine the range of options to improve supply reliability. The second generation version used here calculates the reservoir operations and time dependent rimflow into the Central Valley (CV) on monthly timesteps, providing the needed boundary conditions to California Central Valley Groundwater-Surface Water Simulation Model II.

2.2. Drought Scenarios

Drought scenarios are defined here as surface flow reductions representing scenarios with reductions from 30% to 70%, for periods ranging from 10 years to 60 years, with a 10-year spin-up and a 30-year recovery. The California Central Valley Groundwater-Surface Water Simulation Model II boundary forcing was generated using the California Simulation model II model and historical flow observations of Central Valley rim flows based on the specified reductions corresponding to each scenario. The notation for the set of twelve scenarios is given in Table 1.

Table 1. Drought scenario notation

Specified Scenarios	10 years	20 Years	30 years	60 years
30% reduction	30_10	30_20	30_30	30_60
50% reduction	50_10	50_20	50_30	50_60
70% reduction	70_10	70_20	70_30	70_60

The methodology used to create hypothetical drought scenarios consisted of selecting anomalous hydrologic dry years (in terms of reservoir inflow) from the historic record and appending them to create specified droughts.

The remainder of this report refers to the three drought intensity levels as light (30%), moderate (50%), and severe (70%), noting that the reductions in deliveries are lower than the reductions in reservoir inflows. The specified drought scenarios, reservoir inflows and deliveries are represented in Table 2.

Table 2. Percent cut in deliveries and releases.

Drought Scenario	Percent cut in deliveries	Percent cut in inflows
30_10	10%	10%
30_30	22%	30%
30_70	36%	70%
50_10	10%	10%
50_30	22%	30%
50_70	36%	70%
70_10	10%	10%
70_30	22%	30%
70_60	36%	70%

3.0 Results and Discussion

Stream to groundwater flow, water table height, and groundwater volumetric storage change in response to drought scenarios are dynamically interrelated, along with the change in pumping under the fixed 1973-2003 set of demands, land use, and population. Here the authors discuss the drought responses for four major hydrologic regions: Sacramento, Eastside, San Joaquin, and Tulare, and for the entire Central Valley, with a detailed focus on three drought scenarios, the 30-year moderate drought, the 60-year light drought, and the 60-year severe drought. The appendix provides more detail on the full set of scenarios.

3.1. Surface Diversions

The above defined droughts all begin with the same ten year base period, during which surface diversions across the Central Valley average 10.65 million acre feet (maf) per year. After the 10-year base period, surface diversions in the Central Valley fall 36% during the severe drought scenario. During the moderate drought scenario, surface diversions fall 22percent and during the light drought scenario diversions fall 10percent (Table 3).

Table 3. Impact of droughts on surface diversions on the Central Valley

	Base Period (maf/y)	Severe Drought Impact maf/y	Moderate Drought Impact maf/y	Light Drought Impact maf/y
Central Valley	10.65	-3.78	-2.32	-1.07
Change (%)		-36%	-22%	-10%

The impacts of the droughts are modeled separately for four different regions in the Central Valley, including the Sacramento Basin, Eastside, the San Joaquin Basin, and the Tulare Basin.¹ The regions differ in size and it is easiest to compare impacts across regions on a per acre foot basis (acre feet per acre per year in each region).² On regional a per acre basis, it is apparent that drought scenario impacts are concentrated in the San Joaquin and Tulare Basins. In the severe 60-year drought scenario the Tulare and San Joaquin Basins experience a 0.41 and 0.42 foot per year decline in surface deliveries, compared to the base period (Table 4). In the moderate 30-year and light 60-year drought scenarios, deliveries to the San Joaquin declines about 0.2 and 0.13 feet per year from base year levels. Deliveries to the Tulare basin decline 0.36 and 0.14 feet per year respectively, during the moderate and light drought scenarios (Table 4). The Sacramento Basin and Eastside regions experience comparatively small changes in surface

¹ The Delta is also included as a separate region in the model but the impacts of the drought on that region are very minor and are not included in this report.

² The Central Valley region includes 12.8 million total acres and 6.8 million crop acres. In this study, per acre impacts are measured using total acres. A per acre measure based on cropland would be roughly the size of the measure based on total acres.

diversions during droughts. Sacramento Basin diversions decline 0.22 feet per year in the severe drought, but only change by a slight amount (0.04 to 0.07 feet) for other the two drought scenarios. Eastside diversions are virtually the same during all drought scenarios.

Table 4. Surface diversions in base and drought periods on five sub-regions

	Base Period (af/a/year)	Severe Drought Impact af/a/y	Moderate Drought Impact af/a/y	Light Drought Impact af/a/y
Sacramento	1.04	-0.22	-0.04	0.07
Eastside	0.01	-0.01	-0.01	-0.01
San Joaquin	0.97	-0.42	-0.20	-0.13
Tulare	0.58	-0.41	-0.36	-0.24
Central Valley	0.83	-0.30	-0.18	-0.08
Change (%)		-36%	22%	-10%

3.2. Groundwater Pumping

Farmers in the Central Valley increase groundwater pumping during drought periods to make up for the decline in surface water deliveries. To maintain irrigation levels in the entire Central Valley during droughts, groundwater pumping is increased by 74% in the severe drought, 51percent in the moderate drought, and 27% in the light drought scenario (Table 5).

Interestingly, drought period groundwater pumping more than offsets declines in surface diversions. For example, Central Valley groundwater pumping increases 0.36 feet per year in the severe drought, when surface diversions declined only 0.3 feet per year. In most regions, groundwater pumping goes up between 0.05 and 0.15 feet per year more than irrigation diversions go down. The extra groundwater pumping is needed to make up for dryer climate conditions experienced during drought years. Indeed, groundwater pumping impacts may indicate drought severity better than surface diversion impacts in most regions. For example, Eastside groundwater pumping is increased by 0.12 feet per year in the severe drought scenario and 0.1 and 0.07 feet per year in the moderate and light drought scenarios, while surface diversions remain close to the base period levels (Table 5).

3.3. Stream-to-Aquifer Flows

In normal years, the San Joaquin and Sacramento Rivers are “gaining rivers,” meaning that their flow is increased by movement of water from aquifers that are adjacent to rivers. The flow of water from this groundwater source is decreased during droughts, as groundwater levels decline in these regions. And in the severe drought, ground flows to the San Joaquin River may become reversed with the aquifer drawing water from the river. During moderate and light droughts, the San Joaquin River continues to draw aquifer water, but the amount is diminished.

Sacramento and San Joaquin stream-to-aquifer flows are larger than Eastside and Tulare flows, and tend to dominate the Central Valley averages. These flows help to maintain drought groundwater levels and represent a source of natural recharge in the Sacramento and San

Joaquin Basins. However, the storage benefit of this drought period stream-to-groundwater (relative) flow must be balanced against the corresponding loss of streamflow to the Sacramento and San Joaquin Rivers.

Table 5. Impact of drought on groundwater pumping

	Base Period (af/a/year)	Severe Drought Impact af/a/y	Moderate Drought Impact af/a/y	Light Drought Impact af/a/y
Sacramento	0.17	0.10	0.03	0.00
Eastside	0.42	0.12	0.10	0.07
San Joaquin	0.40	0.51	0.29	0.21
Tulare	0.85	0.85	0.46	0.22
Central Valley	0.49	0.36	0.25	0.13
Change (%)		74%	51%	27%

See Table 6. Alternatively, in normal years the Eastside and Tulare Rivers are “losing rivers” such that they give up flows to replenish aquifers. In drought years, stream-to-aquifer flows diminish, due to a loss of stream-to-aquifer connectivity or to a relative decline in stream levels compared to groundwater levels.

Table 6. Impact of drought on stream to aquifer flows

	Base Period (af/a/year)	Severe Drought Impact af/a/y	Moderate Drought Impact af/a/y	Light Drought Impact af/a/y
Sacramento	-0.44	0.14	0.01	-0.07
Eastside	0.13	-0.06	-0.06	-0.05
San Joaquin	-0.17	0.21	0.06	0.02
Tulare	0.08	-0.02	0.03	0.01
Central Valley	-0.18	0.07	0.02	-0.02
Change (%)		-38%	-10%	13%

3.4. Aquifer Recharge

In normal years the Central Valley aquifers are recharged with excess surface water deliveries and rainwater percolation. In the base period for example, the Central Valley groundwater recharge is 0.76 feet per year compared to groundwater pumping of 0.49 feet per year (Table 7). Excess recharge in normal years helps to maintain groundwater storage during droughts when there is a dramatic decline in recharge. Average recharge across the Central Valley drops 12%, during the light drought scenario, to as much as 41%, during the more severe drought scenario (Table 7).

Across regions, recharge varies in proportion to changes in surface deliveries and rainfall. In the severe drought scenario for example, the Sacramento, San Joaquin and Tulare regions register large declines in aquifer recharge and experience large declines in surface deliveries. The Sacramento and Eastside regions also experience the largest decline in rainfall totals during droughts. This variation in rainfall helps to explain the regional variation in recharge not explained by regional differences in surface deliveries.

Table 7. Impact of drought on aquifer recharge

	Base Period (af/a/year)	Severe Drought Impact af/a/y	Moderate Drought Impact af/a/y	Light Drought Impact af/a/y
Sacramento	0.73	-0.42	-0.32	-0.19
Eastside	0.24	-0.17	-0.17	-0.15
San Joaquin	0.89	-0.39	-0.28	-0.15
Tulare	0.77	-0.26	-0.19	-0.07
Central Valley	0.76	-0.31	-0.24	-0.12
Change (%)		-41%	-32%	-16%

3.5. Changes in Aquifer Storage

Changes in aquifer storage over time is the sum of aquifer withdrawals, including groundwater pumping, minus the aquifer inflows, including stream inflows and irrigation recharge. Changes in boundary flows have an additional, but very minor, impact on storage levels. During the base period (a mix of normal and above normal rainfall years), Central Valley

storage increases by 0.16 feet per year. During the drought scenarios, Central Valley aquifer storage declines from 0.28 feet per year in the light drought scenario to 0.6 feet per year in the severe drought scenario (Table 8).

Table 8. Impact of drought on aquifer storage

	Base Period (af/a/year)	Severe Drought Impact af/a/y	Moderate Drought Impact af/a/y	Light Drought Impact af/a/y
Sacramento	0.73	-0.42	-0.32	-0.19
Eastside	0.24	-0.17	-0.17	-0.15
San Joaquin	0.89	-0.39	-0.28	-0.15
Tulare	0.77	-0.26	-0.19	-0.07
Central Valley	0.76	-0.31	-0.24	-0.12
Change (%)		-41%	-32%	-16%

3.6. Groundwater Levels

Central Valley groundwater levels adjust to changes in storage, rising during the base period and falling during the drought scenarios. During the base period, Central Valley groundwater levels rise 0.98 feet per year, with the Sacramento and San Joaquin Basins increasing by 1.52 feet per year and 1.07 feet per year, respectively, and the Tulare Basin increasing by only 0.11 feet per year. The Central Valley groundwater levels decline by 1.81 feet per year and 3.79 feet per year, respectively, during the light and severe drought scenarios, with substantial variation shown by region (Table 9).

Table 9. Impact drought on groundwater levels

	Base Period (af/a/year)	Severe Drought Impact af/a/y	Light Drought Impact af/a/y
Sacramento	1.52	-2.09	-1.64
Eastside	1.07	-2.34	-1.80
San Joaquin	1.63	-5.12	-2.40
Tulare	0.11	-4.93	-1.65
Central Valley	0.98	-3.79	-1.81

The changes in groundwater level closely match changes in storage levels. In the simple case, assuming a bathtub model of the aquifer, absent confined layers, the annual change in storage (ft) divided by the change in groundwater depth (ft) of an aquifer equals the specific yield of the aquifer. That is, if storage declines by 1 foot and groundwater depth declines 6.25 feet, dividing one by the other results a “specific yield” of 0.16. In fact, the specific yield in the Central Valley is set to be close to 0.16 for all regions in CV2SIM II.

It is apparent that in general and on average, estimated groundwater levels equal the product of estimated storage times the inverse of specific yield in the model. This is indicated in Table 10, which shows changes in storage divided by changes in estimated groundwater level for different regions and time periods in the model. In most cases, the ratio of storage over groundwater is about 0.16, assumed specific yield in the model (Table 10). In the base period for example, the storage to groundwater level ratio is exactly .16. This indicates that groundwater levels during that period vary directly according to changes in storage divided by the specific yield. (Table 10). In other periods and regions, the storage to groundwater ratio varies from 0.16. In the San Joaquin Basin for example, the severe drought period storage to groundwater ratio is 0.13. This indicates that drought period groundwater levels in that region decline more rapidly that suggested by changes in storage and the assumed specific yield.

This is explained by the fact that groundwater wells in the San Joaquin Basin draw water from beneath the impermeable Corcoran Clay layer. In this case, changes in groundwater pressure are likely to be only loosely correlated with changes in aquifer storage.

Table 10. Simple model specific yield implied by changes in storage and groundwater.

	Base Period (ft/ft storage)	Severe Drought Impact (ft/ft storage)	Light Drought Impact (ft/ft storage)
Sacramento	0.16	0.17	0.16
Eastside	0.16	0.17	0.17
San Joaquin	0.16	0.13	0.14
Tulare	0.16	0.17	0.17
Central Valley	0.16	0.16	0.15

Groundwater levels at the end of the severe drought drop 169 feet and levels at the end of the moderate drought fall 143 ft. Levels at the end of the light drought decline 50 ft. During the base period, groundwater levels rise 6.25 feet for every additional foot of storage added to the groundwater. During the drought periods, groundwater levels decline slightly more than 6.25 feet per storage foot on average. Looking at this in more detail, it is apparent that groundwater levels in the Eastside and Tulare Basins decline less and levels in the San Joaquin Basin decline more than 6.25 feet per storage foot.

3.7. Groundwater Decline and Recovery

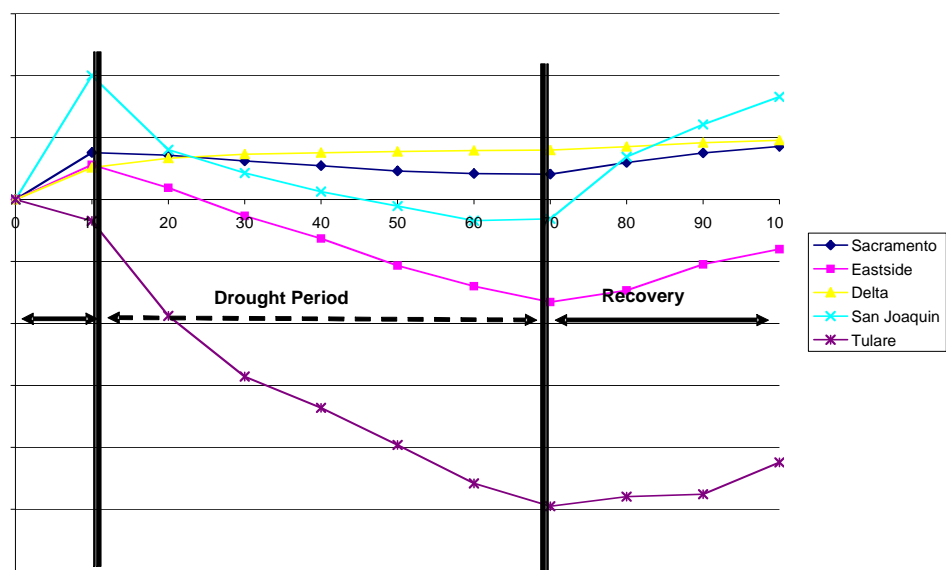
At the end the drought scenarios, groundwater levels across the Central Valley generally decline by less than 200 ft. (Table 11). The cause for groundwater levels in the San Joaquin and Tulare Basins dropping more than the other basins is primarily due to the compensating increase in pumping for these regions. The Tulare Basin experiences the largest decline, ranging from 92 feet in the light drought scenario to 289 feet in the severe drought scenario (Table 11).

Table 11. Groundwater drought decline and recovery

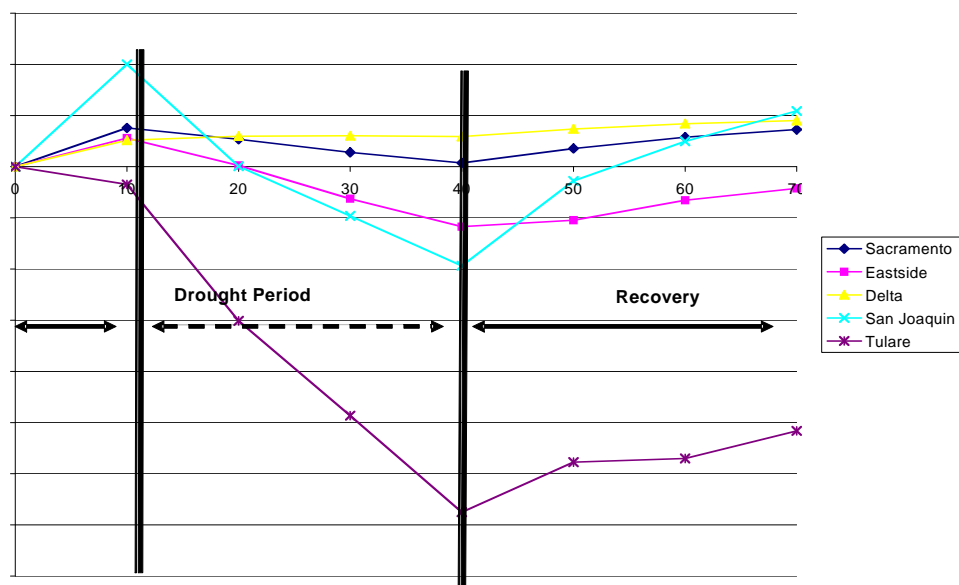
	End Severe 60 year drought	Recovery		Moderate 30 year drought	Recovery		Light 60 year drought (feet)	Recovery	
	(feet)	(feet)	(%)	(feet)	(feet)	(%)	(feet)	(feet)	(%)
Sacramento	-34	25	74%	-27	13	48%	-7	9	129%
Eastside	-76	27	35%	-69	15	22%	-44	17	39%
San Joaquin	-209	78	37%	-157	61	38%	-46	39	85%
Tulare	-289	25	9%	-256	32	12%	-92	14	15%
All	-169	35	20%	-144	29	20%	-50	17	34%

The model runs include a 30-year "recovery period" indicating how aquifers in the Central Valley respond to a return to normal rainfall and irrigation conditions. The Central Valley groundwater reaches 20% of the pre-drought levels after the severe and moderate droughts, and 34% of pre-drought levels after the light drought during this recovery period (Fig. 2). In general, groundwater levels recover most rapidly in the San Joaquin Basin, and less rapidly in the Tulare Basin and Eastside region. The recovery rates suggest that the Tulare Basin would not achieve pre-drought groundwater levels for a very long period of time, if ever. Other regions experience more rapid rates of groundwater recovery. These regions would likely achieve pre-drought groundwater levels relatively rapidly after a drought.

A.



B.



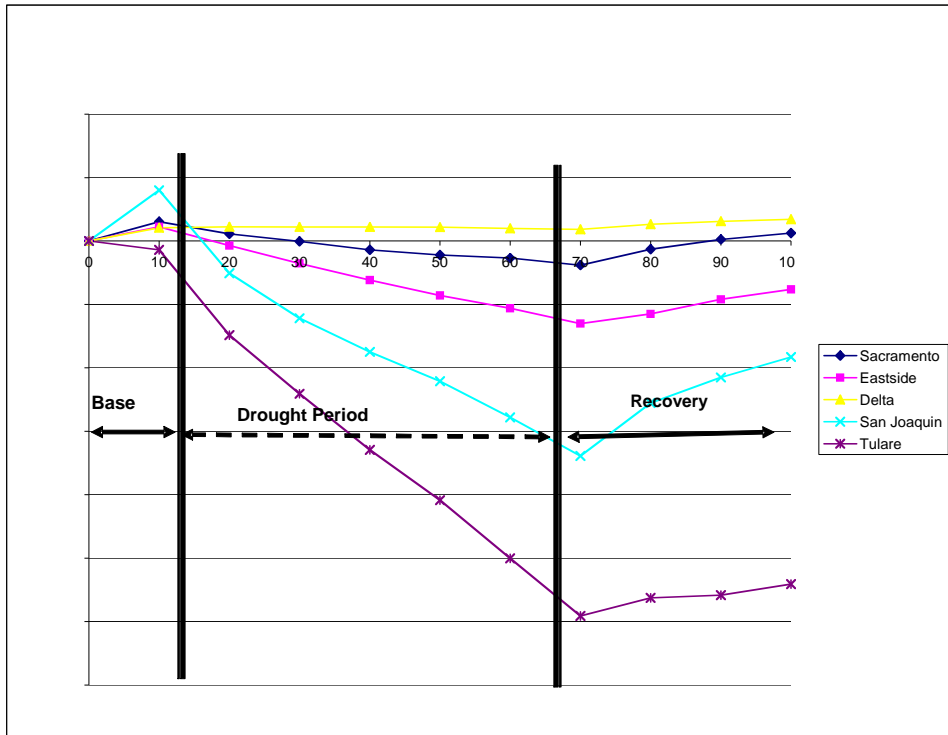


Figure 2 Groundwater trends before during and after A). a moderate 30-year drought B) a slight 60 year drought, and C) a severe 60-year drought.

4.0 Summary and Conclusions

The impacts of global warming and long-term drought are likely to deplete aquifers, increase electricity demand (cooling and pumping) and decrease hydropower generation. This study is intended to illustrate the impacts of climatic events on water storage, and suggests water management techniques to counter some of these adverse impacts. California Central Valley Groundwater-Surface Water Simulation Model and all water allocation models are only partially verified. Many empirical parameters are tuned. Pumping is based on a limited available demand record. Demand is fixed and agriculture does not shift with change in supply.

4.1. Benefits to California

This study is intended to illustrate the impacts of climatic events on water storage, and suggests water management techniques to counter some of these adverse impacts. Understanding the range of drought scenarios will provide policy-makers with new information on system response that are necessary for water planning. Here the authors have indicated the extent of groundwater change under 30 to 70% reductions in surface flow. This work is being expanded with land use change and more detailed levels of drought scenario testing; an important step that will ultimately benefit California water suppliers and users.

5.0 References

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APPENDIX A

Appendix A

A.1 Stream to Groundwater Flow

Stream to groundwater flow is a form of recharge for connected systems. Under normal conditions, the Eastside and Tulare regions are groundwater-gaining (positive) systems, while the Sacramento, San Joaquin, and the Delta regions are groundwater-losing (negative) systems. During 30_10 and 30_60 scenarios, the Eastside and Tulare regions have stream to groundwater flow reductions of 66% and 83% of normal, respectively. Conversely, the Sacramento, Delta, and San Joaquin regions have groundwater to stream flow reductions from normal of 82%, 95%, and 61%, respectively. Under 70_10 and 70_60 scenarios stream to groundwater flow reduction is more dramatic, with flow reductions to 55% and 64% of normal for the Eastside and Tulare regions. Flow reductions in groundwater to stream for the Sacramento and Delta region are 63% and 94% of normal, respectively. However, under this scenario the San Joaquin region loses groundwater to the extent that it shifts flows from groundwater to streams to streams to groundwater. At 70% surface water reduction the San Joaquin loses groundwater to streams for a 10-year drought, but for droughts of duration longer than ten years, the stream to groundwater flow is reversed (Table A.1).

The Central Valley as an aggregated system has stream to groundwater flow reductions of 82%, 75%, and 67% of normal for the effective surface flow reductions of 30%, 50%, and 75%. Table A.1 summarizes these percent changes in groundwater to stream for all cases studied. However, the authors stress that these values are underestimates of the drought reductions, as illustrated in Table A.2 and actual reductions are be substantially larger.

A.2 Pumping Response

To understand the shift in stream to groundwater flow for the drought scenarios that translate into surface flow reductions here, an evaluation of the compensation in supply from surface water to groundwater is needed. C2VSIM was run under the above set of scenarios with a flexible adjustment of pumping levels to meet the historic irrigated crop acreage with fixed water demand.

The impact of shifts in pumping is most pronounced in the San Joaquin and Tulare regions, where a significant amount of irrigated cropping occurs. Figure A.1 shows that the San Joaquin pumping rates increase by 150% for a 10% cut and 260% for a 70% cut, and the Tulare pumping rates increase by 133% for a 10% cut and 177% for a 70% cut. In all cases the duration of the surface flow reductions do not change the pumping rate. This is due to the experimental set up, where the weather conditions, primarily precipitation, and water demands do not change from the 1973-2003 base period. In general the relative increase in pumping followed logically with the cuts in surface water deliveries.

A.3 Storage Change and Head Response

The conjunction of factors, including changes in streamflows and in pumping levels, translates into changes in the water stored in the aquifer expressed here as changes in the pressure head.

The five hydrologic regions within with C2VSIM exhibit large differences in head response due to the different land use and water demand for each region. Table 6 shows water table change for the 30_10, 30_60, 70_10, and 70_60 scenarios. The intensively irrigated San Joaquin and Tulare regions have head drops that are most dramatic, with 24 ft (7.32 m) and 92 ft (28.0 m) water tables drops under the 30_60 scenario, and 164 ft (50.0 m) and 289 ft (88.1 m) drops under the 70_60 scenario, respectively. Recovery after 30 years of normal flow conditions show that water table heads do not return to previous condition, but asymptote toward new, reduced water table levels. In the Sacramento region the water table drop and recovery seem less dramatic, with complete recovery to the previous conditions after 30 years of normal flow.

Table A.1. Percent reduction in stream to groundwater flow during drought scenarios.

30 percent reduction for 10 years							70 percent reduction for 10 years						
Years	Hydrologic Region Sacramento	Eastside	Delta	San Joaquin	Tulare	All	Years	Hydrologic Region Sacramento	Eastside	Delta	San Joaquin	Tulare	All
1 - 10	-1.89	0.06	-0.89	-0.41	0.26	-2.87	1 - 10	-1.41	0.05	-0.86	-0.19	0.21	-2.20
11 - 20	-2.13	0.10	-0.90	-0.52	0.28	-3.17	11 - 20	-1.82	0.11	-0.88	-0.26	0.28	-2.57
21 - 30	-2.42	0.10	-0.95	-0.72	0.35	-3.64	21 - 30	-2.30	0.10	-0.94	-0.57	0.35	-3.36
31 - 40	-2.45	0.09	-0.96	-0.77	0.31	-3.77	31 - 40	-2.38	0.10	-0.95	-0.67	0.31	-3.59
30 percent reduction for 20 years							70 percent reduction for 20 years						
Years	Hydrologic Region Sacramento	Eastside	Delta	San Joaquin	Tulare	All	Years	Hydrologic Region Sacramento	Eastside	Delta	San Joaquin	Tulare	All
1 - 10	-1.94	0.07	-0.88	-0.46	0.27	-2.95	1 - 10	-1.48	0.06	-0.87	-0.21	0.19	-2.32
11 - 20	-1.90	0.07	-0.90	-0.38	0.27	-2.84	11 - 20	-1.14	0.06	-0.86	-0.06	0.19	-1.69
21 - 30	-2.15	0.10	-0.91	-0.49	0.28	-3.16	21 - 30	-1.77	0.11	-0.89	-0.20	0.28	-2.47
31 - 40	-2.43	0.10	-0.96	-0.70	0.35	-3.63	31 - 40	-2.24	0.10	-0.94	-0.49	0.35	-3.21
41 - 50	-2.45	0.09	-0.97	-0.76	0.31	-3.77	41 - 50	-2.33	0.10	-0.95	-0.59	0.32	-3.46
30 percent reduction for 30 years							70 percent reduction for 30 years						
Years	Hydrologic Region Sacramento	Eastside	Delta	San Joaquin	Tulare	All	Years	Hydrologic Region Sacramento	Eastside	Delta	San Joaquin	Tulare	All
1 - 10	-1.88	0.07	-0.88	-0.40	0.26	-2.84	1 - 10	-1.47	0.06	-0.87	-0.22	0.22	-2.28
11 - 20	-1.92	0.06	-0.90	-0.36	0.27	-2.85	11 - 20	-1.53	0.06	-0.89	-0.20	0.22	-2.33
21 - 30	-1.95	0.07	-0.91	-0.39	0.26	-2.92	21 - 30	-1.11	0.06	-0.87	-0.08	0.19	-1.65
31 - 40	-2.14	0.11	-0.92	-0.51	0.28	-3.18	31 - 40	-1.72	0.11	-0.89	-0.18	0.28	-2.40
41 - 50	-2.42	0.10	-0.96	-0.70	0.35	-3.63	41 - 50	-2.21	0.10	-0.94	-0.47	0.35	-3.16
51 - 60	-2.44	0.10	-0.97	-0.76	0.31	-3.76	51 - 60	-2.31	0.10	-0.95	-0.57	0.32	-3.41
30 percent reduction for 60 years							70 percent reduction for 60 years						
Years	Hydrologic Region Sacramento	Eastside	Delta	San Joaquin	Tulare	All	Years	Hydrologic Region Sacramento	Eastside	Delta	San Joaquin	Tulare	All
1 - 10	-1.93	0.06	-0.90	-0.42	0.25	-2.93	1 - 10	-1.44	0.06	-0.87	-0.17	0.19	-2.24
11 - 20	-1.90	0.06	-0.91	-0.35	0.25	-2.84	11 - 20	-1.23	0.06	-0.87	-0.01	0.20	-1.86
21 - 30	-1.91	0.07	-0.90	-0.37	0.27	-2.84	21 - 30	-0.97	0.06	-0.85	0.19	0.19	-1.39
31 - 40	-1.89	0.07	-0.91	-0.36	0.26	-2.83	31 - 40	-1.04	0.06	-0.86	0.19	0.20	-1.46
41 - 50	-1.89	0.07	-0.92	-0.36	0.26	-2.83	41 - 50	-0.97	0.07	-0.85	0.23	0.22	-1.31
51 - 60	-1.92	0.07	-0.92	-0.37	0.27	-2.88	51 - 60	-0.99	0.07	-0.85	0.21	0.17	-1.40
61 - 70	-2.17	0.11	-0.92	-0.51	0.28	-3.21	61 - 70	-1.45	0.12	-0.87	0.16	0.28	-1.76
71 - 80	-2.42	0.10	-0.96	-0.69	0.35	-3.61	71 - 80	-2.06	0.11	-0.92	-0.26	0.35	-2.78
81 - 90	-2.43	0.10	-0.96	-0.74	0.31	-3.72	81 - 90	-2.19	0.11	-0.93	-0.40	0.32	-3.10

Source: N.L. Miller

Table A.2. Change in stream to groundwater flow

30 percent reduction

Drought Length	Hydrologic Region					All
	Sacramento	Eastside	Delta	San Joaquin	Tulare	
10	81%	66%	95%	62%	83%	81%
20	82%	67%	94%	65%	84%	82%
30	82%	66%	95%	58%	84%	81%
60	82%	64%	96%	57%	82%	81%
Average	82%	66%	95%	61%	83%	82%

50 percent reduction

Drought Length	Hydrologic Region					All
	Sacramento	Eastside	Delta	San Joaquin	Tulare	
10	77%	57%	94%	59%	76%	79%
20	73%	55%	93%	52%	73%	76%
30	74%	55%	94%	51%	75%	77%
60	68%	55%	93%	32%	81%	70%
Average	73%	56%	93%	49%	76%	75%

70 percent reduction

Drought Length	Hydrologic Region					All
	Sacramento	Eastside	Delta	San Joaquin	Tulare	
10	65%	55%	93%	38%	65%	69%
20	62%	56%	94%	18%	62%	66%
30	66%	56%	94%	28%	67%	70%
60	58%	54%	95%	-63%	62%	63%
Average	63%	55%	94%	5%	64%	67%

Source: N.L. Miller

Table A.3. Percent increase in pumping during drought scenarios

Scenario	Region				
	3	12	13	19	21
30_10	97%	187%	153%	117%	122%
30_60	100%	196%	154%	118%	124%
50_10	148%	175%	179%	201%	154%
50_60	157%	199%	183%	214%	159%
70_10	171%	296%	204%	194%	165%
70_60	170%	298%	205%	192%	164%

Source: N.L. Miller

Table A.4. Hydrologic region water table response to surface flow reductions.

30 percent reduction for 10 years						
Year	Hydrologic Region					All
	Sacramento	Eastside	Delta	San Joaquin	Tulare	
10	-0.4	-7.4	2.9	-7.9	-19.2	-9.5
20	3.1	-5.5	5.2	13.7	-15.8	-2.7
30	5.6	0.8	7.2	22.0	-15.5	0.3
40	6.9	2.8	8.3	27.7	-5.5	5.9

70 percent reduction for 10 years						
Year	Hydrologic Region					All
	Sacramento	Eastside	Delta	San Joaquin	Tulare	
10	-9.1	-14.5	-0.2	-79.3	-76.7	-48.8
20	-1.0	-9.9	4.4	-10.6	-47.5	-21.2
30	2.8	-3.0	6.6	7.4	-46.0	-15.5
40	4.9	-0.4	7.9	17.7	-35.5	-8.5

30 percent reduction for 60 years						
Year	Hydrologic Region					All
	Sacramento	Eastside	Delta	San Joaquin	Tulare	
10	-0.8	-7.4	3.0	-18.1	-30.7	-16.0
20	-2.7	-16.5	4.3	-16.3	-50.4	-24.4
30	-4.3	-23.8	4.8	-20.0	-60.5	-30.0
40	-5.9	-32.5	5.2	-22.0	-72.5	-36.1
50	-6.8	-39.2	5.5	-23.9	-85.0	-42.0
60	-7.0	-44.3	5.6	-14.5	-92.4	-43.5
70	-3.2	-40.6	6.7	8.4	-89.3	-36.5
80	-0.1	-32.2	8.0	18.1	-88.5	-32.7
90	2.0	-27.2	8.8	25.0	-78.4	-26.4

70 percent reduction for 60 years						
Year	Hydrologic Region					All
	Sacramento	Eastside	Delta	San Joaquin	Tulare	
10	-9.5	-14.8	0.8	-56.5	-67.3	-40.8
20	-15.5	-28.9	0.7	-92.4	-113.6	-68.5
30	-22.1	-42.0	0.6	-103.9	-157.8	-90.7
40	-26.2	-54.1	0.5	-115.5	-197.5	-110.4
50	-28.6	-64.2	-0.4	-140.0	-243.4	-134.5
60	-34.2	-76.4	-1.1	-163.6	-288.9	-159.2
70	-21.6	-68.7	2.9	-91.9	-274.5	-135.3
80	-14.0	-57.3	5.3	-65.6	-272.3	-126.3
90	-8.9	-49.3	6.7	-47.8	-263.7	-117.3

Source: N.L. Miller

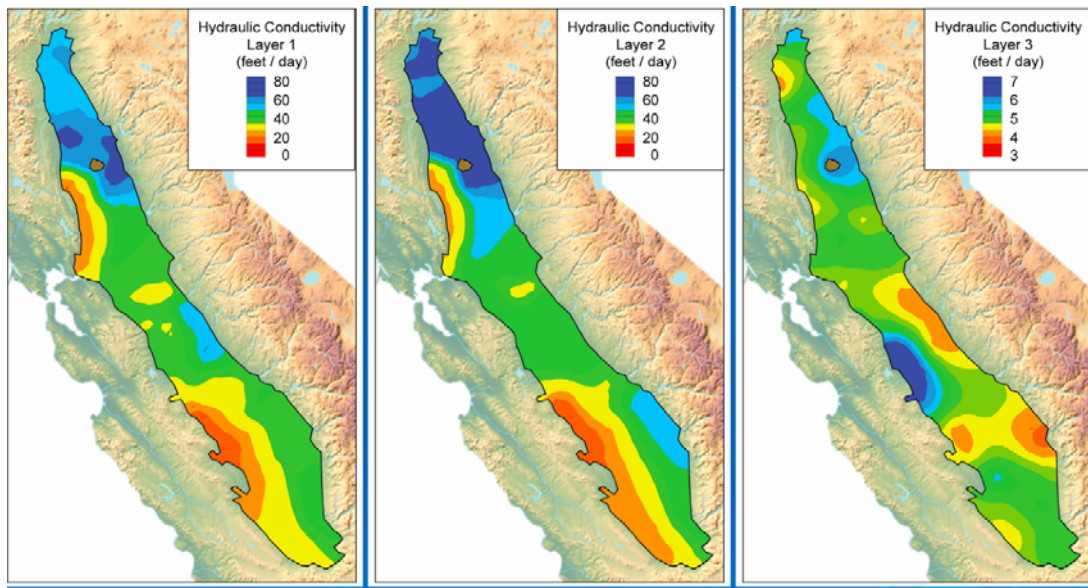


Figure A.1 Hydraulic conductivity distributions in the C2VSIM model.

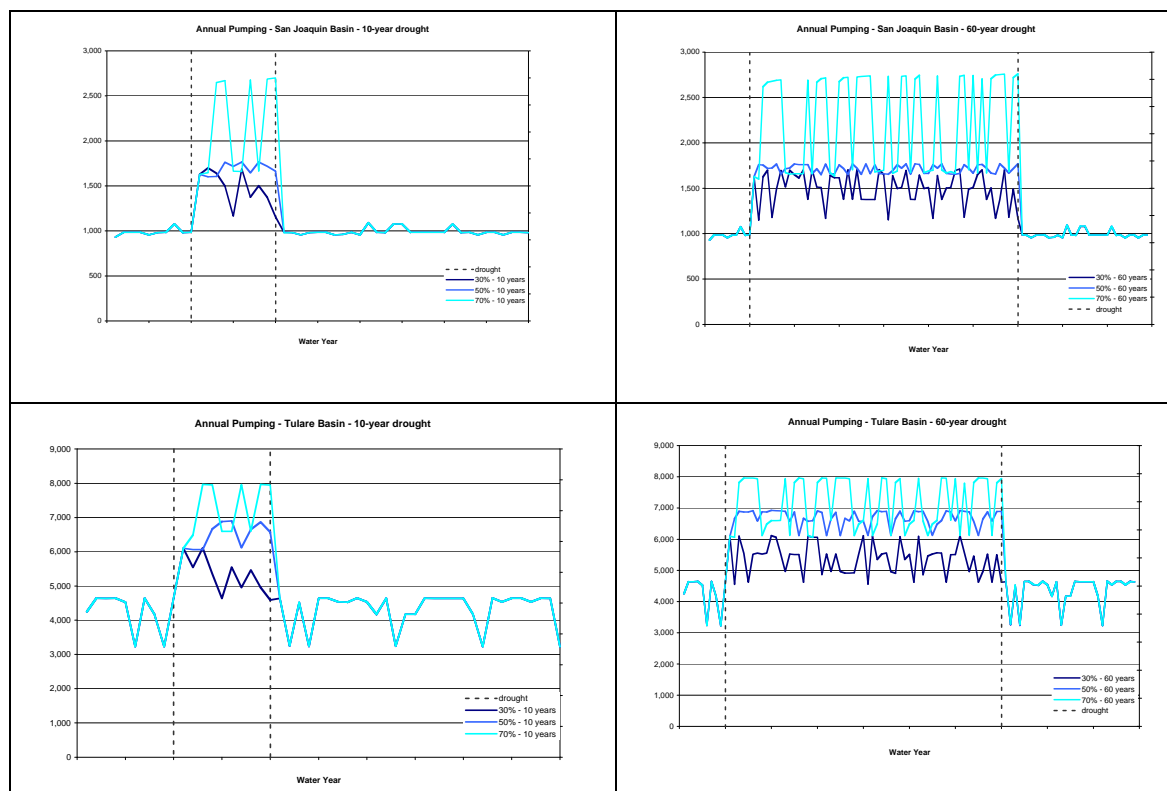


Figure A.2. Jan Joaquin and Tulare regional pumping changes required for drought compensation